Coordination of Overcurrent Protection and Fault Ride through Requirements of Doubly Fed Induction Generator in a Wind Turbine

M.Nayeripour, M.M.Mansouri

Abstract: Due to power system stability in high penetration of wind turbines during grid disturbances, the Fault Ride Though (FRT) requirements have been developed to remain connected the wind turbines during the grid voltage sags. Usually the FRT requirements are implemented with crowbar protection that protects the rotor side converter, but the generator windings have noticeable over current during grid voltage disturbances. Therefore, the stator current of doubly fed induction generator is investigated in grid voltage sags, and then the overcurrent settings of stator winding are analyzed. Main focus of this paper is coordination of overcurrent protection with FRT requirements. The overcurrent curves and time settings are discussed in agreement with FRT requirements.

Keywords: Doubly Fed Induction Generator (DFIG), Protection Coordination, Fault Ride Through (FRT), Overcurrent.

I. INTRODUCTION

Renewable energy researches are in the top priority of studies and wind energy is on the first ranking of them. Variable Speed Wind Turbines (VSWTs) have more economical and technical interests today and they will give more parts of the energy markets in upcoming future. Doubly Fed Induction Generators is used widely in the VSWTs [1-3].

DFIGs have some advantages like need to lower power electronic converters related to turbine rated power. But DFIGs have some issues that must be consider for their best utilization. One of them is DFIGs sensitivity to grid disturbances, especially grid sag voltages. Sag voltage due to grid fault at Point of Common Coupling (PCC) is sensed by DFIG and causes to increasing the DFIG currents. As power electronic converters have limit power rating, this high current can harm the Rotor Side Converter (RSC). One way to protection of RSC is its blocking and disconnecting the turbine from the grid [4-6].

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With increasing of wind turbine penetration, disconnection of wind turbines has negative impact on the overall grid stability in grid disturbances; because sag voltage is sensed with all wind turbines relatively and grid will loss considerable wind power in each disturbance. Therefore, the grid utilities have established new grid codes for connection of Distributed Energy Resources (DERs) so that they must stay connected to grid and ride through the sag voltage of grid faults as define FRT characteristics [7].

Many researches have been done for development and improvement of FRT capability of VSWT-DFIG yet. Must of solutions are using crowbar protection which the rotor current is conducted to resistors via power electronics switches and in some cases the RSC is blocked [4-6][8-9].

Although, some research have been done for overcurrent protection of wind turbine in grid [1][8][10-13] but overcurrent protection of DFIG winding during voltage sag has not been considered yet. Therefore, main focus of this paper is over current protection of DFIG stator winding, because coordination of over current protection has some conflicts with FRT requirements as:

- VSWT-DFIGs must have FRT capability in voltage sags due to grid faults. This requirement causes to slowing (or blocking) the protection system especially for overcurrent protection [14-15].
- Usually crowbar protection is used for protection of RSC from over voltage and overcurrent in grid voltage dip [5-6][11], but there is not any plan for protection of DFIG windings in grid fault at transient duration.
- Satisfying FRT capability and grid connection codes causes some problems for DFIG and converter protections like overcurrent protection [8].
- Different parameters affect the amplitude and time domain of winding overcurrent rating in grid faults, but the FRT characteristics is a fixed characteristic [10][14-15].
- The FRT characteristic is a voltage–time characteristic which has definite time setting but the overcurrent curves are time inverse curves [20-22].
- Base on FRT requirements, the stator winding must

withstand high overcurrent in grid voltage dip.

Therefore, a dip investigation on stator current is done at the PCC voltage dip, then coordination of OC protection of DFIG and FRT requirements are discussed analytically. Then some parameters that affect coordination between them are discussed.

II. DFIG Behavior in Grid Fault

The transient equations of DFIG are obtained from (1) to (15) in time domain [16].

$$R_s = r_s I_{3\times 3} \quad (1)$$

$$R_r = r_r I_{3\times 3} \quad (2)$$

$$\vec{v}_s = [v_{as} \quad v_{bs} \quad v_{cs}]^T \quad (3)$$

$$\vec{v}_r = [v_{ar} \quad v_{br} \quad v_{cr}]^T \quad (4)$$

$$\vec{i}_s = [i_{as} \quad i_{bs} \quad i_{cs}]^T \quad (5)$$

$$\vec{i}_r = [i_{ar} \quad i_{br} \quad i_{cr}]^T \quad (6)$$

$$\vec{v}_s = R_s \vec{i}_s + d\vec{\psi}_s / dt + j\omega_s \vec{\psi}_s \quad (7)$$

$$\vec{v}_r = R_r \vec{i}_r + d\vec{\psi}_r / dt + j(\omega_s - \omega_r)\vec{\psi}_r \quad (8)$$

$$\vec{\psi}_s = L_s \vec{i}_s + L_m \vec{i}_r \quad (9)$$

$$\vec{\psi}_r = L_m \vec{i}_s + L_s \vec{i}_r \quad (10)$$

$$L_s = \begin{bmatrix} L_{\ell s} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{\ell s} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{\ell s} + L_{ms} \end{bmatrix} \quad (11)$$

$$L_r = \begin{bmatrix} L_{\ell r} + L_{mr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & L_{\ell r} + L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{\ell r} + L_{mr} \end{bmatrix} \quad (12)$$

$$L_m = L_{sr} \begin{bmatrix} cos(\theta_m) & cos(\theta_m + \frac{2\pi}{3}) & cos(\theta_m - \frac{2\pi}{3}) \\ cos(\theta_m - \frac{2\pi}{3}) & cos(\theta_m) & cos(\theta_m + \frac{2\pi}{3}) \\ cos(\theta_m + \frac{2\pi}{3}) & cos(\theta_m - \frac{2\pi}{3}) & cos(\theta_m) \end{bmatrix} \quad (13)$$

$$T_e = \frac{p}{2} \vec{i}_s^{\,T} \frac{\partial L_m}{\partial \theta_m} \vec{i}_r \quad (14)$$

$$J \frac{d^2\theta_m}{dt^2} = T_w - T_e \quad (15)$$

Which θ_m is the rotor angle, J is total inertia momentum of turbine, and T_w is the wind torque. When a fault occurs in the grid, a sag voltage is seen in different PCCs. Amplitude of this voltage sag depends to some parameters like fault resistance, Short Circuit Ratio (SCR) at the fault point, and type of fault [17], and distance (impedance) between PCCs and fault point [10]. The SCR of PCC also strongly affects the current of DFIG in grid faults.

The stator current is equal to (19) in three phase to ground grid fault [16].

$$\sigma = 1 - L_{sr}^2 / (L_{\ell r} L_{\ell s}) \quad (16)$$

$$\begin{aligned} L'_s &= L_{\ell s} + L_{\ell r} L_{sr} / (L_{\ell r} + L_{sr}) \\ L'_r &= L_{\ell r} + L_{\ell s} L_m / (L_{\ell s} + L_{sr}) \end{aligned} \quad (17)$$

$$T_{s'} = L'_s / R_s , T_{r'} = L'_r / \quad (18)$$

$$\vec{i}_s = \frac{\sqrt{2}V_s}{jX'_s}[e^{-t/T_{s'}} - (1-\sigma)e^{j\omega_s t} e^{-t/T_{r'}}] \quad (19)$$

The maximum stator current is equal to (20) that R_{cb} is crowbar resistance [16].

$$i_{s,\max} \approx \frac{1.8V_s}{\sqrt{X'^2_s + R^2_{cb}}} \quad (20)$$

As the X'_s and R_{cb} are small, the stator current has considerable over current in grid disturbances.

III. FRT REQUIREMENTS

The stator voltage of DFIG sees the voltage sag in grid faults, thus the DFIG output power reduces while the input mechanical power is constant. The rotor current increases to several per unit and DFIG absorbs large reactive power that gets worse the voltage drop. The rotor currents also increase to several per unit and causes over current for RSC. The overvoltage of DC link between RSC and GSC is also occurs. For prevention of converters damages, normal operation of WT-DFIG is cancelled. Disconnecting the turbine form grid means loss of generation for several minutes and more to re-startup and synchronization [18].

For prevention of huge generation loss in high wind turbine penetrations, the *Fault Ride Through* capability has been defined that enforces wind turbines to remain connected and synchronous to grid above the defined FRT curve. FRT curve is different in countries as shown in Fig.1 .

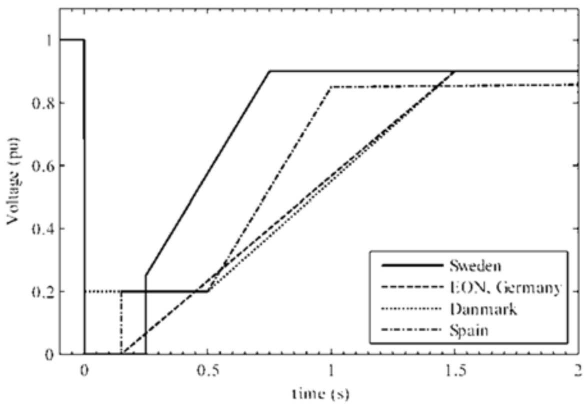

Fig.1 FRT characteristics in some different countries

The VSWT-DFIG must stay connected for area above the defined curves. The FRT capability usually is implemented with crowbar protection as shown in Fig.2 [4][6][9]. The FRT Code of Danish grid code is used in this paper.

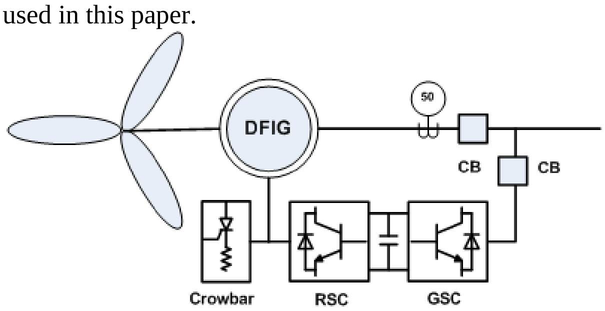

Fig.2 Crowbar Circuit

The crowbar protection is used for protection of RSC from over current and over voltage of rotor winding due to grid voltage dip. But the rotor and stator windings still have over current during the fault transient. As the stator and rotor current are coupled to together, the stator OC protection is investigated in this paper. A Circuit Breaker (CB) and OC are considered for this purpose as shown in Fig.2.

IV. OVER CURRENT PROTECTION

Typical protections of DFIG are over / under voltage(27/59), over current(50/51), over / under frequency protection(81), speed matching to within 5% (15), phase-sequence or negative sequence voltage (47), negative sequence current (46), reverse power (32) and winding temperature protection [14-15][19][20].

The DFIG is protected via a circuit breaker with current of 2-3 times of rated current [8]. OC protection of DFIGs is implemented by fuse or time delay relays. Usually time characteristics of this protection are time inverse. Standard defined curves for OC protection is shown in Table I and Table II [20-21].

TABLE I. OC CURVES- IEC 60255

Relay Characteristics	Equation
Standard Inverse (SI)	$t = TMS \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS \frac{80}{I_r^2 - 1}$

Ir = (I/Is), where *Is* = relay setting current
TMS = Time multiplier Setting

TABLE II. OC CURVES- NORTH AMERICAN IDMT

Relay Characteristics	Equation
IEEE Moderately Inverse (MI)	$t = \frac{TD}{7}\left(\frac{0.0515}{I_r^{0.02} - 1} + 0.0114\right)$
IEEE Very Inverse (VI)	$t = \frac{TD}{7}\left(\frac{19.61}{I_r^2 - 1} + 0.491\right)$
Extremely Inverse (EI)	$t = \frac{TD}{7}\left(\frac{28.2}{I_r^2 - 1} + 0.1217\right)$

TD = Time Delay

V. FRT & OC COORDINATION

As DFIG currents reach several per unit in grid voltage disturbances, OC requirements must be satisfied in coordination with FRT requirements.

For realization FRT requirements, crowbar circuit and control methods are used for RSC protection but a serious over current remains in DFIG windings that they must be protected by OC relay as shown in Fig.2 .

FRT requirements have a definite and fixed time setting independent of current, but the DFIG current depends to SCR, fault type, rotor speed and DFIG time constants. Therefore coordination between these two protections is hard and is some case seems impracticable.

The main factors for overcurrent settings are thermal rating, startup current and overload limits. The thermal rating of DFIG is high enough for satisfying the FRT requirement [16][19]. Therefore the startup over current is the main lower limit in OC coordination and upper limit is overload rating of machine and FRT requirements. As crowbar circuit has minimum delay of quarter to one cycle (5-2010ms), another issue for OC setting is covering this delay.

VI. SIMULATION

A WT-DFIG is simulated in radial connection to grid as shown in Fig.3 in PSCAD/EMTDC [11] .

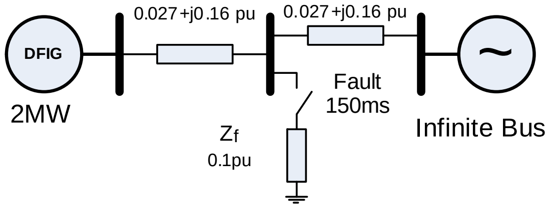

Fig.3 WT-DFIG connection for sag voltage study

The studied DFIG parameters are as Table III.

TABLE III. DFIG PARAMETERS

Parameter	Value	Parameter	Value
P_n	*2 MW*	N_s/N_r	*0.63*
V_s	*690 V*	*H*	*3.5 s*
f_s	*50 Hz*	L_m	*3.953pu*
L_{ls}	*0.105pu*	R_s	*0.005pu*
L_{lr}	*0.100pu*	R_r	*0.0055pu*

The stator voltage and rotor current are shown in Fig.4 without crowbar protection for $R_{fault} = 0.1pu$, $t_{fault} = 0.15 Second$, and $S_{lip} = 0.05$.

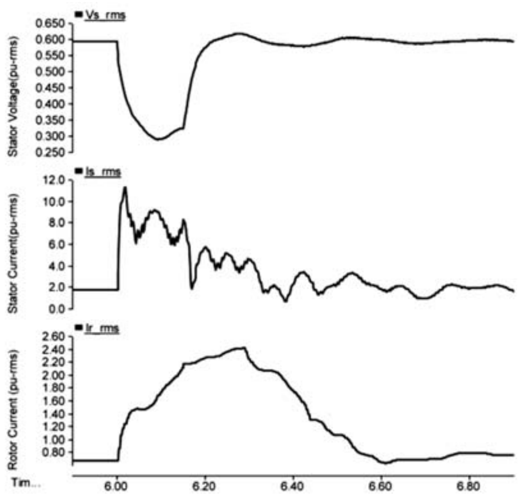

Fig.4 The stator voltage and rotor current without crowbar

For FRT capability, vector control of generator flux and crowbar protection is used as shown in Fig.2. The WT passes the voltage dip of grid fault according to FRT curve for $R_{fault} = 0.1pu$, $t_{fault} = 0.15Second$, and $S_{lip} = 0.05$ as shown in Fig.5 .

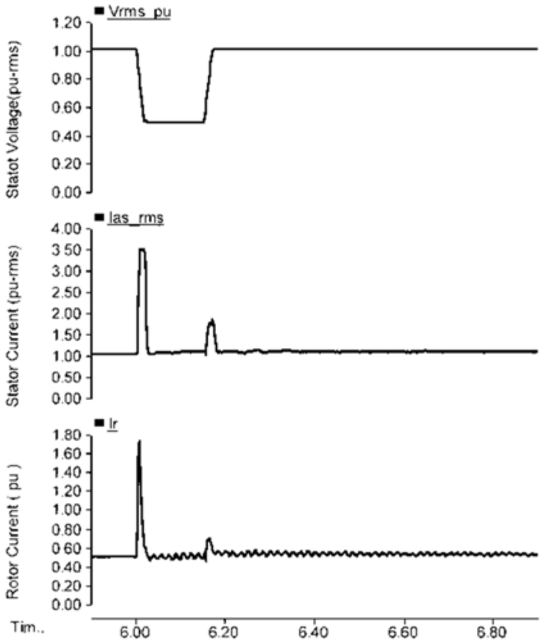

Fig.5 The stator voltage and rotor current with crowbar

A overcurrent protection setting is specified with amplitude setting, TMS/Td setting and curve type. The overcurrent amplitude of stator winding is determined by fault type and WT behavior. The operation time of OC protection is determined by FRT curve. Therefore, only TMS/TD must be calculated for coordination. The Time Multiplier Scale (TMS) or Time Delay (TD) is calculated with shown algorithm at Fig.6.

In the proposed algorithm, different voltage dips are simulated in the first step. Then FRT code requirements and DFIG overload considerations are compared. Finally, the TMS or TD settings for each voltage dip simulation are calculated.

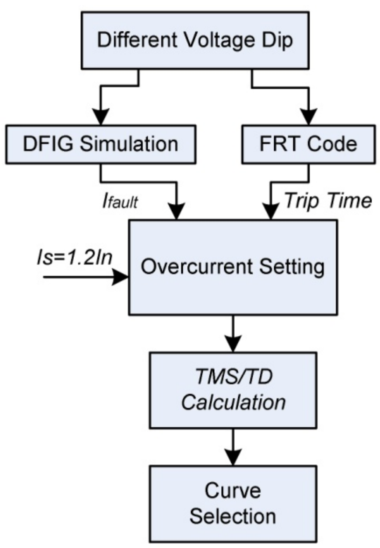

Fig.6 The TMS/TD calculation algorithm

For overcurrent setting Is, TMS/TD, and curve type must be determined. Therefore, some simulations were done for three phase voltage dip base on Danish FRT requirements according to Table IV.

TABLE IV. VOLTAGE DIP AND TRIP TIME BASE ON DANISH FRT CODE

	Case1	Case2	Case3
Voltage Dip (pu)	0.8	0.6	0.15
Trip Time (Second)	0.500	0.8	1.5
Fault Resistance (pu)	0.026	0.069	0.43

TMS/TD values were calculated for three voltage dip 80%, 60%, and 15%. Considering startup current, DFIG thermal capacity, and FRT requirements, minimum OC settings for different curves are shown in Table V.

TABLE V. OVER CURRENT SETTINGS FOR *IS=1.2IN*

	Curve	*TMS/TD*
Voltage Dip=0.8 pu => Trip Time=500mS & Ifault=6.7 pu	IEC(SI)	0.1385
	IEC(VI)	0.211
	IEC(EI)	0.2743
	IEEE(MI)	2.6128
	IEEE(VI)	3.7231
	IEEE(EI)	4.5799
Voltage Dip=0.6 pu => Trip Time=800mS & Ifault=4.4 pu	IEC(SI)	0.1719
	IEC(VI)	0.2015
	IEC(EI)	0.1836
	IEEE(MI)	3.2487
	IEEE(VI)	3.5919
	IEEE(EI)	3.3783
Voltage Dip=0.15 pu => Trip Time=1500mS & Ifault=1.15 pu	IEC(SI)	0.0300
	IEC(VI)	0.0167
	IEC(EI)	0.0060
	IEEE(MI)	0.5703
	IEEE(VI)	0.1713
	IEEE(EI)	0.1199

It is predictable that the worst case is 80% voltage dip that OC must not have operation in less than 500mS. The results are shown in Fig.7 for different curves.

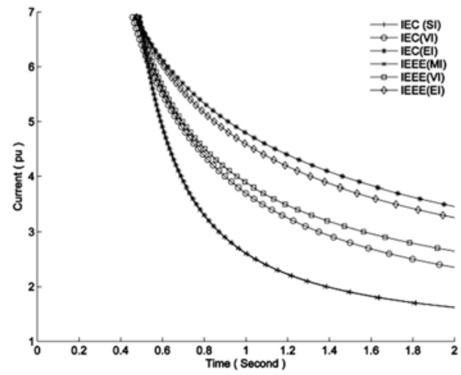

Fig.7 Different curves for FRT compatibilities

Usually IEC-SI or IEC-VI is recommended for machine protections [19][21] but the windings must be connected in very high overcurrent (about 4-6 pu) of winding current in 500ms according to FRT code. Therefore, the IEC-EI curve is obtained the best curve for FRT requirements compatibility. This curve is suitable for extremely high current in very short time.

VII. CONCLUSION

As stator winding must remain connected to grid in grid disturbances in a DFIG base wind turbine according to FER codes, overcurrent protection of a 2MW DFIG wind turbine is simulated for different grid faults. Base on calculated currents and time limits of FRT curve, the best overcurrent curve and setting is calculated.

This paper results show that the IEC-EI curve is the best curve for FRT code compatibility.

For high voltage sags, the stator winding has high overcurrent and thermal tension. It seems that some crowbars that limit the stator current, is better than the crowbars in the rotor side which protect only the RSC.

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